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Ultra-low cycle fatigue performance evaluation of the miniaturized low yield strength steel shear panel damper

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ABSTRACT

Merited as rapid assembly and replacement, the miniaturization design of the low yield strength steel shear panel damper has been attracted more attention of researchers. Functioned as damping structure, enough response displacement realized by large deformation capacity with enough low cycle fatigue life is very important for seismic design. Several types of tests are conducted to clarify the performance of the damper. The deformation capacity and low-cycle fatigue performance of the damper material are investigated through monotonic and constant amplitude cyclic shear tests. The deformation capacity of the actual damper affected by width to thickness ratio is verified by incremental amplitude cyclic shear tests. Combined with the constant amplitude cyclic shear tests of the damper, the failure degradation process from damper material to damper structure is systematically analyzed. According to the seismic design requirement, the deformation capacity of the damper when the fatigue cycle number is between 10 and 30 is discussed in detail. Both the accurate prediction and the simple and rapid prediction on the applicable deformation capacity of the damper are proposed according to the analysis of low-cycle fatigue life. This study provides an in-depth understanding of the damage evolution of a miniaturized damper which plays a significant role in the optimization design and practical application of the damper.

1. Introduction

Shear panel damper (SPD) has been widely adopted in seismic design. The earthquake energy is dissipated by the reciprocating shear plastic deformation of the metallic panel. Ordinary carbon steel (Q235, yield strength 235 MPa) [1], pure aluminum [2] and low yield strength steel (LYS) [3] are general selected as the damper material by the present researchers for engineering application. The energy consumption capacities per unit mass of these materials were analyzed and compared by Zhang [4]. The test results showed that the large deformation capacity of LYS gave it a distinct advantage over other damper materials. Hence, LYS is the preferred material for miniaturization and lightweight design of SPD.

The miniaturization of SPD is conducive to saving building materials and expanding the scope of application. Different damping structures can be realized by different combinations of SPDs. The traditional yielding core of the braces is substituted by several SPDs, a new buckling restrained brace was proposed by Piedrafita [5]. Since the energy dissipation capacity of the new brace strongly depends on the mechanical performance of SPDs, large deformation capacity with sufficient fatigue life is crucial to the new brace design.

To utilize the maximum deformation capacity of the LYS is the key feature for the miniaturization design of the low yield strength steel shear panel damper (LYSPD). Hence, continuous attention was paid to improve the deformation capacity of the damper in the past researches. Perforated panels [6–8] and edge shape optimized panels [9–10] were tried to alleviate the stress concentration of SPD. Meanwhile, the deformation capacity of SPD is hardly to be improved obviously by the aforementioned methods.

In general, the deformation capacity of SPD can be improved greatly by using the flanges instead of the shape optimization of the panel. Furthermore, even when the flanges were adopted, the deformation capacity of SPD is also hardly to be improved by the shape optimization of panel. The deformation capacity of SPD can be improved greatly by the stiffeners at the upside and bottom of the panel when the corner stress concentration was alleviated greatly [11–12]. Thus, the optimization on the boundary condition was one of the key factors to ensure the large deformation capacity of LYSPD.

Based on the optimized boundary condition, the corner stress concentration is still serious if the panel is thick. On the opposite, the

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out-of-plane buckling is prone to be produced which affects the deformation capacity of LYSPD. The cross stiffeners [13] and outer buckling restrain plates [14] were designed to suppress the buckling. Meanwhile, the improvement on the deformation capacity was very limit. Hence, choosing an appropriate width to thickness ratio is a key point to improve the deformation capacity and fatigue life of LYSPD.

Several theories such as Kirchhoff, Reissner [15] and Mindlin [16] were adopted to analyze the mechanical performance of the panels. The buckling phenomenon of the thin panels was usually analyzed by Kirchhoff theory while the shear deformation of the moderate panels or thick panels was considered in Reissner and Mindlin theory. Buckling strength or shear strength of LYSPD in elastic and plastic range was focused on in these theories. No literatures were reported that the maximum deformation capacity and the fatigue life can be predicted by these theories. Therefore, experiment is the sole effective method to investigate the relation between the width to thickness ratio and deformation capacity of LYSPD.

Researches on the fatigue degradation process from damper material to damper structure under large plastic response were still lacking. The low cycle performance of LYSPD was investigated by Peter [17] by applying the cyclic tension-compression tests on LYS with maximum strain 7%. When fatigue cycle number was the same, the strain amplitude of reference [17] is smaller than that of LYSPD [18]. A hang upside down phenomenon was observed, the fatigue performance of the damper material was poorer than that of the damper structure. Different failure mechanism was the key factor lead to this phenomenon. The inhomogeneous deformation results from necking accelerated the failure process of the material specimen under tension-compression loading while the uniform deformation can be obtained in the shear loading. Therefore, the low cycle fatigue performance of LYSPD should be evaluated by the torsional tests instead of tension-compression tests.

There are many factors affect the fatigue performance of LYSPD which include mean strain, loading sequence, strain speed, welding embrittlement, the multi-axial stress, structure parameter, strain amplitude and so on. The first three factors were negligible according to the experimental results of Zhang [18–19]. Whatever the local and global buckling in the thin panel or the large plastic shear deformation in the thick panel, the multi-axial stress or strain is inevitable during the operation of LYSPD. Welding embrittlement is also affected by the multi-axial stress. It is very difficult to investigate the fatigue performance of LYSPD affected by these factors independently. Hence, the global failure of LYSPD is concentrated on in this research. Accordingly, plastic strain life is adopted to evaluate the low cycle fatigue performance of the LYSPD based on the Manson-Coffin and Miner rule.

There are general three types of LYS material such as LYS100 (yield strength 100 MPa), LYS160 (yield strength 160 MPa) and LYS225 (yield strength 225 MPa). Characterized with the largest deformation capacity among these three materials, LYS100 was focused on in this study. First of all, fatigue performance of LYS when the fatigue cycle number is between 10 and 30 was investigated through cyclic torsional tests. Subsequently, three different panel thicknesses were designed to clarify the relation between the width to thickness ratio and the deformation capacity of LYSPD. Finally, combined with the constant amplitude fatigue test results in previous research, the whole failure degradation process from LYS to LYSPD was evaluated. This study presents the life assessment for LYS with the use of strain criterion for low cycle fatigue evaluation and design of LYSPD.

2. Test procedure

2.1. Specimens

2.1.1. Material specimens

Thin-walled and solid cylinder specimens are two typical standard specimens in torsion tests. Stress gradient can be neglected if the thickness of thin-walled cylinder specimen is thin enough. Thus, the accurate shear stress in small strain range can be obtained. However, the buckling is prone to be produced under reciprocating large plastic shear strain amplitude. Not only the stress but also the strain fatigue life cannot be predicted accurately in the large plastic range. As the applicable strain amplitude and fatigue life are the focuses in this study, the solid cylindrical specimen is adopted. The material specimen is shown in Fig. 1, the effective diameter and length are 10 mm and 100 mm respectively. The maximum shear stress and strain at the outer edge of the specimen can be calculated from the angle-moment curve of the torsion testing machine using the following equation:

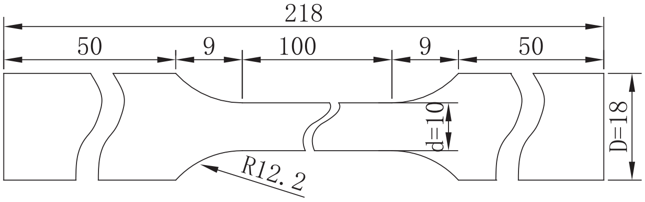

Fig. 1. Material specimen.

$$\gamma_m = \frac{\theta \cdot \pi d}{360^\circ \cdot l} \times 100\% \qquad (1)$$

$$\tau_{max} = \frac{3}{4}\frac{T}{W_t}, \qquad (2)$$

where γ_m is the shear strain of material specimen, θ is the torsion angle, d is the effective diameter, l is the effective length, τ_{max} is the shear stress at the outer edge of the specimen, T is the torsion moment, and $W_t = \frac{\pi}{16}d^3$ is the torsion section modulus.

2.1.2. Shear panel damper

The geometries of LYSPD are shown in Fig. 2. It was composed of two parts, the shear panel and the ribs located at the left and right sides of the panel. Both of these two parts were made from LYS. To avoid the overlap of the plastic hinge and the corner stress concentration result from welding, the upside and downside parts of the shear panel were thickened. The effective length and width of the shear panel were both 120 mm. Three different thicknesses (t = 6, 8, 12 mm) were selected to investigate and compare the deformation capacity or the fatigue performance of LYSPD (see Sheet 1).

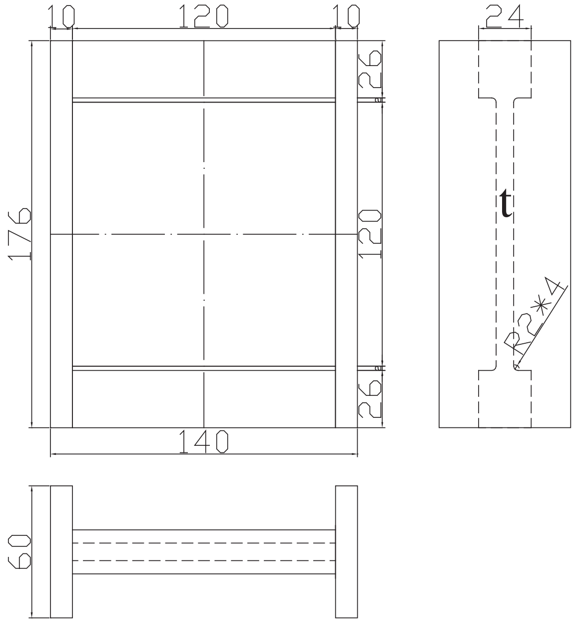

Fig. 2. Structure specimen.